A Giant Step: from Milli- to Micro-arcsecond Astrometry
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Testing planet formation models with Gaia μas astrometry

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Abstract. In this paper, we first summarize the results of a large-scale double-blind tests campaign carried out for the realistic estimation of the Gaia potential in detecting and measuring planetary systems. Then, we put the identified capabilities in context by highlighting the unique contribution that the Gaia exoplanet discoveries will be able to bring to the science of extrasolar planets during the next decade.

Keywords. planetary systems, astrometry, methods: data analysis, methods: numerical, stars: statistics

1. Introduction

Despite a few important successes (e.g., Bean *et al.* 2007, and references therein), astrometric measurements with a mas precision have so far proved to be of a limited value when employed as either a follow-up tool or for independent searches of planetary-mass companions orbiting nearby stars (e.g., Sozzetti 2005, and references therein).

In several past exploratory works (Casertano *et al.* 1996; Lattanzi *et al.* 1997, 2000; Sozzetti *et al.* 2001, 2003), we have shown in some detail what space-borne astrometric observatories with μas-level precision, such as Gaia (Perryman *et al.* 2001), can achieve in terms of search, detection and measurement of extrasolar planets in the mass range from Jupiter-like to Earth-like. In those studies we adopted a qualitatively correct description of the measurements that each mission will carry out, and we estimated detection probabilities and orbital parameters using realistic, non-linear least squares fits to those measurements.

Those exploratory studies, however, need updating and improvements. In the specific case of planet detection and measurement with Gaia, we have thus far largely neglected the difficult problem of selecting adequate starting values for the non-linear fits, using perturbed starting values instead. The study of multiple-planet systems, and in particular the determination of whether the planets are coplanar—within suitable tolerances—is incomplete. The characteristics of Gaia have changed, in some ways substantially, since our last work on the subject (Sozzetti *et al.* 2003). Last but not least, in order to render the analysis truly independent from the simulations, these studies should be carried out in double-blind mode.

We present here a substantial program of double-blind tests for planet detection with Gaia (preliminary findings were presented by Lattanzi *et al.* (2005)), with the three-fold goal of obtaining: a) an improved, more realistic assessment of the detectability and measurability of single and multiple planets under a variety of conditions, parametrized by the sensitivity of Gaia; b) an assessment of the impact of Gaia in critical areas of planet research, and dependence on its expected capabilities; and c) the establishment of several Centers with a high level of readiness for the analysis of Gaia observations relevant to the study of exoplanets.

2. Double-blind tests campaign results

We carry out detailed simulations of Gaia observations of synthetic planetary systems and develop and utilize in double-blind mode independent software codes for the analysis of the data, including statistical tools for planet detection and different algorithms for single and multiple Keplerian orbit fitting that use no a priori knowledge of the true orbital parameters of the systems.

Overall, the results of our earlier works (e.g., Lattanzi *et al.* 2000; Sozzetti *et al.* 2001, 2003) are essentially confirmed, with the fundamental improvement due to the successful development of independent orbital fitting algorithms applicable to real-life data that do not utilize a priori knowledge of the orbital parameters of the planets. In particular, the results of the T1 test (planet detection) indicate that planets down to astrometric signatures $\alpha \simeq 25$ μas, corresponding to ~ 3 times the assumed single-measurement error, can be detected reliably and consistently, with a very small number of false positives (depending on a specific threshold for detection). The results of the T2 test (single-planet orbital solutions) indicate that: 1) orbital periods can be retrieved with very good accuracy (better than 10%) and small bias in the range of $0.3 \lesssim P \lesssim 6$ yr. In this period range the other orbital parameters and the planet's mass are similarly well estimated. The quality of the solutions degrades quickly for periods longer than the mission duration, and the fitted value of P is systematically underestimated; 2) uncertainties in orbit parameters are well understood; 3) nominal uncertainties obtained from the fitting procedure are a good measure of the actual errors in the orbit reconstruction. Modest discrepancies between estimated and actual errors arise only for planets with extremely good signal (errors are overestimated) and for planets with very long period (errors are underestimated); such discrepancies are of interest mainly for a detailed numerical analysis, but they do not address adequately the assessment of Gaia's ability to find planets and our preparedness for the analysis of perturbation data. The results of the T3 test (multiple-planet orbital solutions) indicate that 1) over 70% of the simulated orbits under the conditions of the T3 test (for every two-planet system, periods shorter than 9 years and differing by at least a factor of two, $2 \leqslant \alpha/\sigma_\psi \leqslant 50$, $e \leqslant 0.6$) are correctly identified; 2) favorable orbital configurations (both planets with periods $\leqslant 4$ yr and astrometric signal-to-noise ratio $\alpha/\sigma_\psi \geqslant 10$, redundancy of over a factor of 2 in the number of observations) have periods measured to better than 10% accuracy over 90% of the time, and comparable results hold for other orbital elements; 3) for these favorable cases, only a modest degradation of up to 10% in the fraction of well-measured orbits is observed with respect to single-planet solutions with comparable properties; 4) the overall results are mostly insensitive to the relative inclination of pairs of planetary orbits; 5) over 80% of the favorable configurations have $i_{\rm rel}$ measured to better than 10 degrees accuracy, with only mild dependencies on its actual value, or on the inclination angle with respect to the line of sight; 6) error estimates are generally accurate, particularly for fitted parameters, while modest discrepancies (errors are systematically underestimated) arise between formal and actual errors on $i_{\rm rel}$.

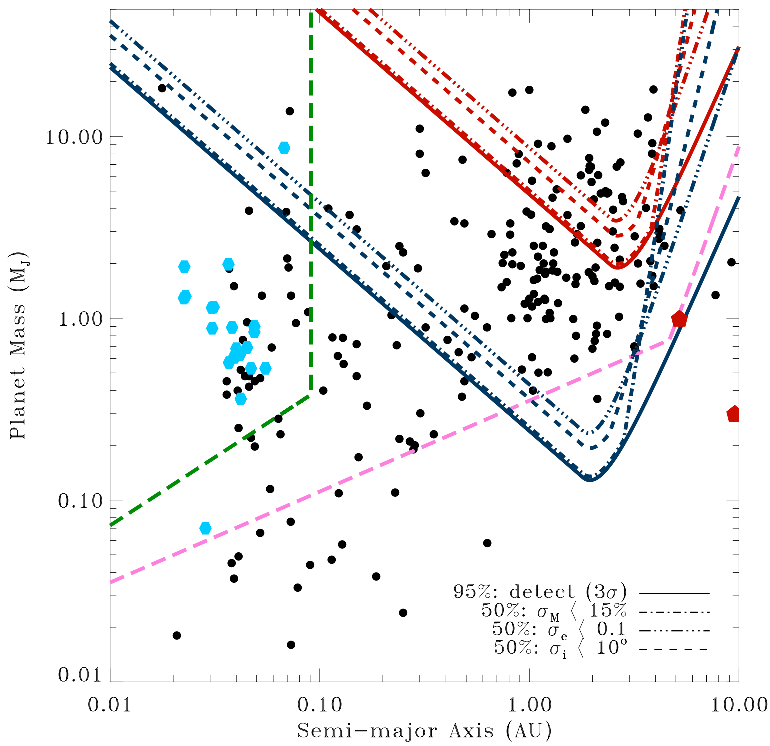

Figure 1. Gaia discovery space for planets of given mass and orbital radius compared to the present-day sensitivity of other indirect detection methods, namely Doppler spectroscopy and transit photometry. Red curves of different styles (for completeness in planet detection and orbit measurement to given accuracy) assume a 1-$M_\odot$ G dwarf primary at 200 pc, while the blue curves are for a 0.5-$M_\odot$ M dwarf at 25 pc. The radial velocity curve (pink line) is for detection at the $3 \times \sigma_{\rm RV}$ level, assuming $\sigma_{\rm RV} = 3$ m s^{-1}, $M_\star = 1 M_\odot$, and 10-yr survey duration. For transit photometry (green curve), $\sigma_V = 5$ milli-mag, $S/N = 9$, $M_\star = 1\ M_\odot$, $R_\star = 1\ R_\odot$, uniform and dense (> 1000 data points) sampling. Black dots indicate the inventory of exoplanets as of October 2007. Transiting systems are shown as light-blue filled pentagons. Jupiter and Saturn themselves are shown as red pentagons.

3. The Gaia expectations

In Fig. 1 we show Gaia's discovery space in terms of detectable and measurable planets of a given mass and orbital separation around stars of a given mass at a given distance from Earth (see caption for details). From this Figure, one would then conclude that Gaia could discover and measure massive giant planets ($M_p \gtrsim 2-3\ M_{\rm J}$) with $1 < a < 4$ AU orbiting solar-type stars as far as the nearest star-forming regions, as well as explore the domain of Saturn-mass planets with similar orbital semi-major axes around late-type stars within 30-40 pc. These results can be turned into a number of planets detected and measured by Gaia, using Galaxy models and the current knowledge of exoplanet frequencies. By inspection of Tables 1 and 2, we then find that Gaia could measure accurately thousands of giant planets, and accurately determine coplanarity (or not) for a few hundred multiple systems with a favorable configuration.

In conclusion, Gaia's main strength continues to be the ability to measure actual masses and orbital parameters for possibly thousands of planetary systems. The Gaia data have the potential to a) significantly refine our understanding of the statistical properties of extrasolar planets: the predicted database of several thousand extrasolar planets with

Table 1. Number of giant planets that could be detected and measured by Gaia, as a function of increasing distance. Star counts are obtained using the Besancon model of stellar population synthesis (Bienaymé *et al.* 1987), while the Tabachnik & Tremaine (2002) model for estimating planet frequency as a function of mass and orbital period is utilized.

Δd (pc)	$N_\star$	Δa (AU)	ΔM_p (M_J)	$N_{\rm d}$	$N_{\rm m}$
0-50	1×10^4	1.0 - 4.0	1.0 - 13.0	1400	700
50-100	5×10^4	1.0 - 4.0	1.5 - 13.0	2500	1750
100-150	1×10^5	1.5 - 3.8	2.0 - 13.0	2600	1300
150-200	3×10^5	1.4 - 3.4	3.0 - 13.0	2150	1050

Table 2. Number of multiple-planet systems that Gaia could potentially detect, measure, and for which coplanarity tests could be carried out successfully.

Case	Systems
Detection	~ 1000
Orbits and masses to better than 15-20% accuracy	$\sim 400 - 500$
Successful coplanarity tests	~ 150

well-measured properties will allow for example to test the fine structure of giant planet parameters distributions and frequencies, and to investigate their possible changes as a function of stellar mass with unprecedented resolution; b) help crucially test theoretical models of gas giant planet formation and migration: for example, specific predictions on formation time-scales and the role of varying metal content in the protoplanetary disk will be probed with unprecedented statistics thanks to the thousands of metal-poor stars and hundreds of young stars screened for giant planets out to a few AUs; c) improve our understanding of the role of dynamical interactions in early as well as long-term evolution of planetary systems. For example, the measurement of orbital parameters for hundreds of multiple-planet systems, including meaningful coplanarity tests will allow to discriminate between various proposed mechanisms for eccentricity excitation; d) aid in the understanding of direct detections of giant extrasolar planets. For example, actual mass estimates and full orbital geometry determination for suitable systems will inform direct imaging surveys about where and when to point, in order to estimate optimal visibility, and will help in the modeling and interpretation of giant planets' phase functions and light curves; e) provide important supplementary data for the optimization of the target selection for Darwin/TPF: for example, all F-G-K-M stars within the useful volume ($\sim$ 25 pc) will be screened for Jupiter- and Saturn-sized planets out to several AUs, and these data will help probing the long-term dynamical stability of their Habitable Zones, where terrestrial planets may have formed, and maybe found.

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